AD P001071

FREE-FLIGHT ROCKET GUIDANCE WITH THE SPINNING PLUG NOZZLE

W. E. Judnick and A. H. Samuel
Battelle-Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

INTRODUCTION

The spinning plug nozzle (SPN) has a direct effect on the flow of the rocket exhaust gases. It acts like a gyroscope to restore the angle between the rocket axis and the spinning plug axis to zero. Thus, when the rocket body axis becomes misaligned with the plug axis, due to external moments acting upon the rocket, leading to inaccuracy, the SPN restores the alignment and minimizes the flight path error.

The SPN concept was invented by Captain John E. Draim and was documented in his Massachusetts Institute of Technology thesis in 1969(1). Missile Command (MICOM) later funded an exploratory prototype development with Booz/Allen to demonstrate hardware and the feasibility of using off-the-shelf materials such as standard bearings. Lockheed was MICOM's technical monitor/consultant on the program. Experiments by Draim(1) and Freeman(2) have shown that the theoretical SPN effect can be achieved in practice. The restoring moment on the rocket is sizable. In 1980, Battelle's Columbus Division completed a contract for Lockheed Missile and Space Company on the military applications of the SPN.(3) Battelle developed its SPIN (Spinning Plug In Nozzle) model to help evaluate the concept. The software was first applied to three different rocket types: the 2.75-in., the Multiple Launch Rocket System (MLRS), and the OATS. This paper summarizes this work at Battelle. In the authors' personal opinion, the concept shows considerable promise and merits wider exposure and consideration within the control theory community.

The remainder of the paper is organized into three additional sections. The SPIN model is briefly described in the next section. Highlights of the initial simulation results for the 2.75-in., MLRS, and OATS rockets are then presented. We end with some brief conclusions and recommendations of a more general nature.

The authors wish to gratefully acknowledge the participation of R. T. Batcher and J. H. Ott, both of Battelle's Washington Operations, in the described study. The advice and support of J. A. Freeman of the Lockheed Missile and Space Company were most valuable and are much appreciated. We also wish to thank Captain Draim for a copy of his thesis.

SPIN MODEL METHODOLOGY

Rockets destroy targets by hitting a vulnerable area, which may be smaller (High Energy Anti Tank, HEAT) or larger (Improved Conventional Munitions, ICM) than the physical area of the target. A rocket aimed at a point will miss it due to

the accumulation of errors. Let the miss distance be S. This value can be compared to the target vulnerable area dimensions. Military worth will generally increase as S decreases. The miss distance, S, is a good measure of effectiveness which can be related to kill probabilities or to numbers of rockets required in the case of area targets.

The SPN can correct only a portion of the errors of a rocket system. Our approach quantifies the degree to which SPN corrects the following errors:

(1) Initial error angle, ALPHAZ, the angle between the rocket's axis and the true aim vector as the rocket clears the launcher

(2) Initial angular velocity (pitch and yaw), DALFZ, the time derivative of the error angle at the same instant

(3) Externally imposed rotational moment, EMM, acting on the rocket axis, due to cross wind (surface wind, rotor wash, etc.).

The simplest model of the physical process is as follows. The SPN produces a restoring force proportional to the angle between the plug axis and the rocket axis. This force produces a torque that acts on the rocket. In the simplest representation, there are no out-of-plane forces, no damping, and the lever arm is constant. In these circumstances, the SPN would produce a simple harmonic oscillation of the rocket around the true direction, in the plane defined by the original rocket and plug axes.

However, we are not interested in the direction in which the rocket is pointing, as such, but rather in the miss distance. If it is valid to assume that the rocket moves in the direction of its axis, and that the plug axis is pointed at the target, then the increment to the miss distance in an infinitesimal time interval will be proportional to the sine of the angle between the axes and to the instantaneous rocket velocity. It is thus possible to cumulate the miss distance along the trajectory. In fact, there is a value of the miss distance S corresponding to each possible target distance, though, of course, one is primarily interested in the value corresponding to the actual distance.

For the simple case defined above, miss distance can be obtained in closed-form, which turns out to be sinusoidal. An integrated solution in series form has been obtained for the case in which the lever arm of the restoring force increases at a constant rate. This also is an oscillating function. However, in more general cases of military significance, an algebraic solution is not to be expected. The calculations described in this paper are therefore based on numerical integration.

The SPIN model essentially follows the rocket over its trajectory. At each time interval, the following operations are performed. In the notation a prime indicates a new value being computed from the old value and current values of other variables.

(1) The miss distance is incremented according to the formula

$$S' = \int_0^T \frac{V*SIN(ALPHA)}{SINB}\, dt$$

where V = rocket velocity

ALPHA = rocket pitch-yaw angle between rocket axis and plug axis (In the cylindrically symmetrical rocket we do not distinguish pitch and yaw.)

SINB = angle between trajectory plane and target plane, an input

In the numerical integration, the miss distance is cumulated over many small time intervals in accordance with the following algorithm

$$S' = S + V*SIN(ALPHA)*DT/SINB$$

$$S(0) = 0$$

where DT is the input time interval of integration.

(2) The distance X traveled by the rocket is also cumulated by

$$X' = X + V*DT$$

$$X(0) = 0$$

The calculation is terminated when X reaches XZERO, the input distance to the target.

(3) The rocket velocity is updated according to the formula

$$V' = V + (ACCEL + GRAV*SINB - QDRAG*V*V)*DT$$

$$V(0) = VZERO \text{ (an input)}$$

where ACCEL = acceleration due to rocket thrust, an input

GRAV = acceleration due to gravity, an input

QDRAG = drag coefficient of rocket for forward movement in units of 1/length, an input

This formula is appropriate if the target plane is horizontal, and must be modified if it is not.

(4) The rocket pitch-yaw angle ALPHA is updated by integrating its derivative DERALF, the corresponding angular velocity:

$$ALPHA' = ALPHA + DERALF*DT$$

$$ALPHA(0) = ALPHAZ \text{ (an input)}$$

(5) The angular velocity, in turn, is updated by accounting for three types of angular acceleration:

$$DERALF' = DERALF + (RESTOR + EMM - DPG)*DT$$

$$DERALF(0) = DALFZ \text{ (an input)}$$

where RESTOR = angular acceleration due to the SPN restoring force

EMM = angular acceleration due to externally imposed moments (e.g., surface wind)

DPG = angular deceleration due to damping.

(6) The calculation of RESTOR is given by the formulas:

$$RESTOR = RESMOM/ZI$$

$$RESMOM = RESFOR*ARM$$

$$RESFOR = ZKR*ALPHA$$

where RESMOM = restoring moment or torque

ZI = rocket moment of inertia in pitch-yaw dimension

RESFOR = restoring force

ARM = lever arm, distance from point of application of force to rocket center of gravity

ZKR = restoring force per unit angle, an input property depending only on the geometry of the SPN, an input

(7) The lever arm length varies with time because the rocket's center of gravity moves forward as fuel is consumed. It is updated by:

$$ARM' = ARM + DARM*DT$$

$$ARM(0) = ARMZ \text{ (an input)}$$

where DARM = velocity of rocket center of gravity relative to the rocket, an input.

(8) The externally imposed moment arises from the noncoincidence of the center of pressure from impinging wind with the center of gravity. The distance between them is EARM which, like

ARM, must be updated. EARM is the lever arm for the force coefficient ECONST, an input. Thus:

$$\mathrm{EMM} = \mathrm{ECONST*EARM/ZI}$$

$$\mathrm{EARM}' = \mathrm{EARM} + \mathrm{DARM*DT}$$

$$\mathrm{EARM(0)} = \mathrm{EARMZ}\ \text{(an input)}$$

(9) The deceleration due to damping is proportional to the angular velocity:

$$\mathrm{DPG} = \mathrm{DAMP*DERALF}$$

where DAMP is an input damping constant that is characteristic of the system.

(10) Finally, the moment of inertia also must be updated, because it is reduced by fuel consumption:

$$\mathrm{ZI}' = \mathrm{ZI} + \mathrm{DI*DT}$$

$$\mathrm{ZI(0)} = \mathrm{ZIZ}\ \text{(an input)}$$

where DI = rate of change of moment of inertia, an input.

These operations constitute the mathematical structure of the SPIN model, implemented on Battelle's Control Data Corporation 6500 computer. Figure 1 represents a rocket in flight with some of the more important relationships as defined as above. The SPIN model is a simplified representation in which the following processes are not represented: curvature of the trajectory; out-of-plane forces and motions; and components of the miss distance that cannot be affected. Thus, the SPIN model cannot be used for engineering calculations. It does indicate, however, with what is believed to be adequate accuracy, to what extent the SPN can correct the errors that it does affect, as a function of SPN design, rocket design, and environmental parameters.

Typical SPIN runs required less than three seconds of central processing unit time, thus permitting the extensive exploratory studies. Outputs of the SPIN program include:

(1) At frequent user-determined intervals, instantaneous values of X, S, T, ALPHA, V, and DERALF

(2) At the end of simulated flight:

a. Maximum S along the trajectory
b. Number of times S crosses zero
c. Maximum ALPHA along the trajectory
d. Number of times ALPHA crosses zero
e. "Probability of hit": the fraction of time intervals for which $S \leq R$, after traveling a minimum standoff distance (R is an input target dimension)

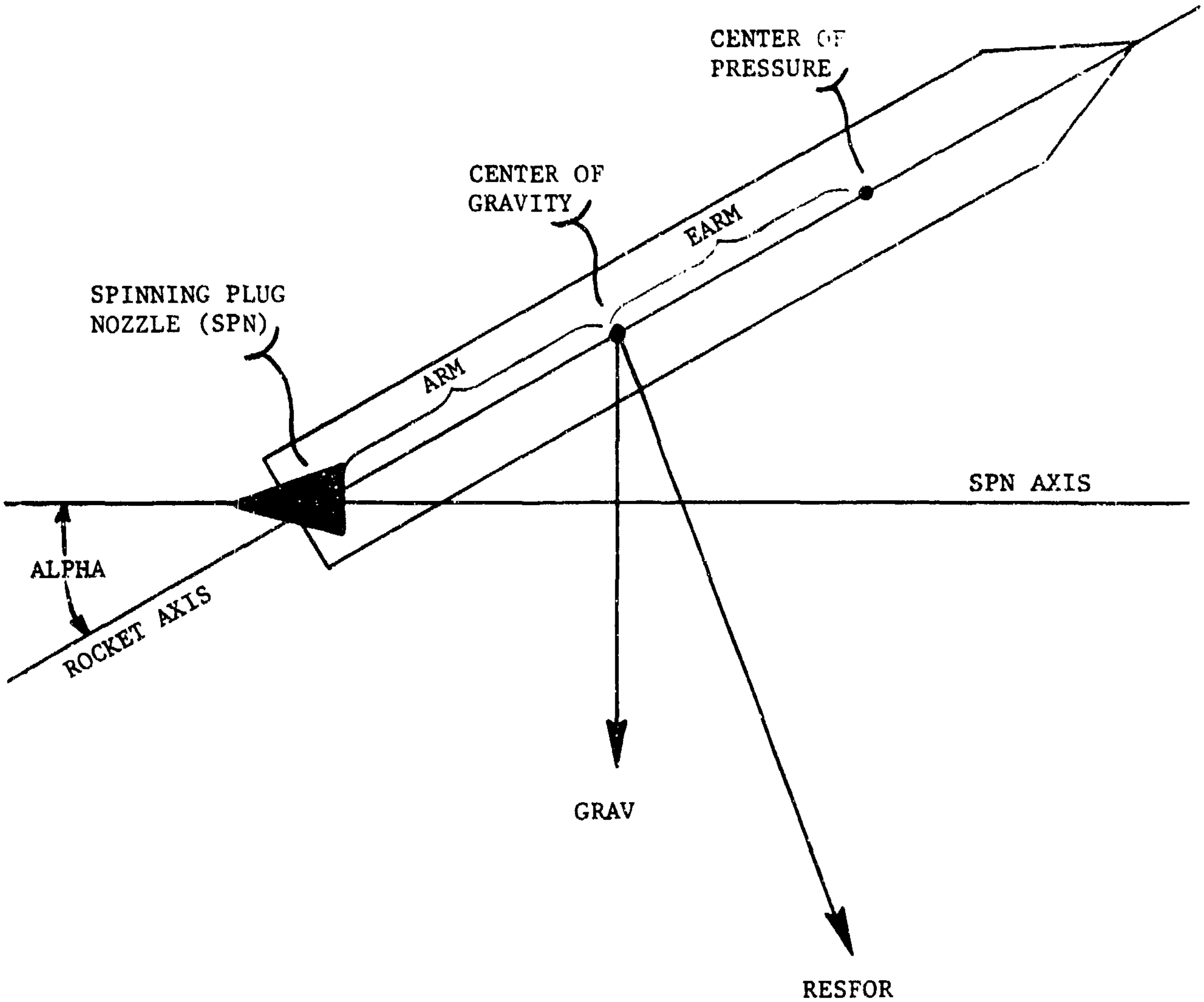

FIGURE 1. SPN SYSTEM TRANSIENT RESPONSE

Some distances and angles have been exaggerated from their more typical values for ease of illustration.

f. Final velocity V
g. Final miss distance S in meters
h. Final miss distance S in milliradians.

The most important outputs for the determination of military worth are 2g and 2h. The other outputs assist analysts in developing an understanding of the nonlinear processes involved, particularly the relative influences of design and environmental factors.

Table 1 summarizes SPIN model inputs representing the base cases for the conceptual rockets considered in this paper.

SELECTED SIMULATION RESULTS

To investigate the potential application of the SPN to the 2.75-in. Folding Fin Aircraft Rocket (FFAR), several runs of the SPIN (Spinning Plug In Nozzle) model were made. The primary figure of merit used for the conceptual system represented in these runs was the deflection error in meters, firing at a slant range of 4 km. Several early runs were devoted to the base case, with the primary conclusion being that performance is extremely sensitive to the factor DAMP, the damping of angular motion due to air.

The sensitivity to DAMP was confirmed in other SPIN runs in which the burn time of the rocket was extended from the usual 1.06 seconds to two and three times as long. The idea behind these runs was that the longer the SPN was working, the better the result might be. Of course, with a heavier rocket during the earlier part of the flight, the more difficult it would be for the SPN to influence its course. Therefore, there is an optimal burn time for any given plug and propellant quantity.

Extension of the burn time from 1.06 seconds to 2.12 seconds, and then to 3.18 seconds had a salutary effect on accuracy. For a graphical summary, see Figure 2. In essence, to get the most benefit from the plug and rocket, the whole rocket has to be redesigned. Of course, getting an SPN to fit within such a small diameter rocket is a noteworthy design problem.

As shown in Figure 3, miss distance is primarily in the negative direction, due to the prop wash external moment imposed during the first 5 meters of flight. The curve shown is sinusoidal with damped frequency and damped amplitude.

To investigate the potential application of the SPN to the MLRS system, the error budget published in the Special Study Group report[4] was examined. Each error source was classified as to whether or not the SPN could be expected to appreciably reduce that type of error. As shown in Table 2, this classification showed that several quantitatively important error sources fell into the "correctable" category. The contribution of these correctable error sources is about 6 mils. Because the total from all error sources is roughly 10, the estimated circular error probable (CEP) for a fully corrected MLRS is 8 mils.

TABLE 1. BASE CASE PARAMETER INPUTS

MK66 FFAR (2.75-In.)	MLRS	OATS
ACCEL = 0 to 67 g's in 0.04 sec, 67 to 97 g's in next 0.94 sec, drop to 0 in next 0.09 sec	ACCEL = 600 m/sec^2	ACCEL = 222.22 m/sec^2
ALPHAZ = 0.018 radians	ALPHAZ = 0.004 radians	ALPHAZ = 0.008 radians
ARMZ = 0.7 m	ARMZ = 1.6 m	ARMZ = 0.23 m
DALFZ = 0.0 radians/sec	DALFZ = 0.0 radians/sec	DALFZ = 0.0 radians/sec
$1.0 \leq$ DAMP $\leq 14.0\ sec^{-1}$	DAMP = 1.0 sec^{-1}	DAMP = 20 sec^{-1}
DARM = 0.127 m/sec	DARM = 0.305 m/sec	DARM = 0.0237 m/sec
DI = -1.5 $kg\text{-}m^2/sec$	DI = -95.56 $kg\text{-}m^2/sec$	DI = -0.05985 $kg\text{-}m^2/sec$
DT = 0.0004 or 0.0012 sec	DT = 0.001 sec	DT = 0.001 sec
EMM = 0.01158 $radians/sec^2$ during first 5 m, 0.0 otherwise	EMM = 0.01158 $radians/sec^2$	EMM = 1.603526*EARM/ZI $radians/sec^2$
GRAV = 9.81 m/sec^2	GRAV = 9.81 m/sec	GRAV = 0.0 m/sec
QDRAG = 0.000166 m^{-1}	QDRAG = 0.0004 m^{-1}	QDRAG = 0.00055 m^{-1}
SINB = 0.05	SINB = 0.7071	SINB = 1.0
VZERO = 63.84 m/sec	VZERO = 50 m/sec	VZERO = 23.1 m/sec
XZERO = 4000 m	XZERO = 675 m	XZERO = 1000 m
ZIZ = 3 $kg\text{-}m^2$	ZIZ = 280 $kg\text{-}m^2$	ZIZ = 0.4843 $kg\text{-}m^2$
ZKR = 1450 Newtons/radian	ZKR = 1500 Newtons/radian	ZKR = 400 Newtons/radian

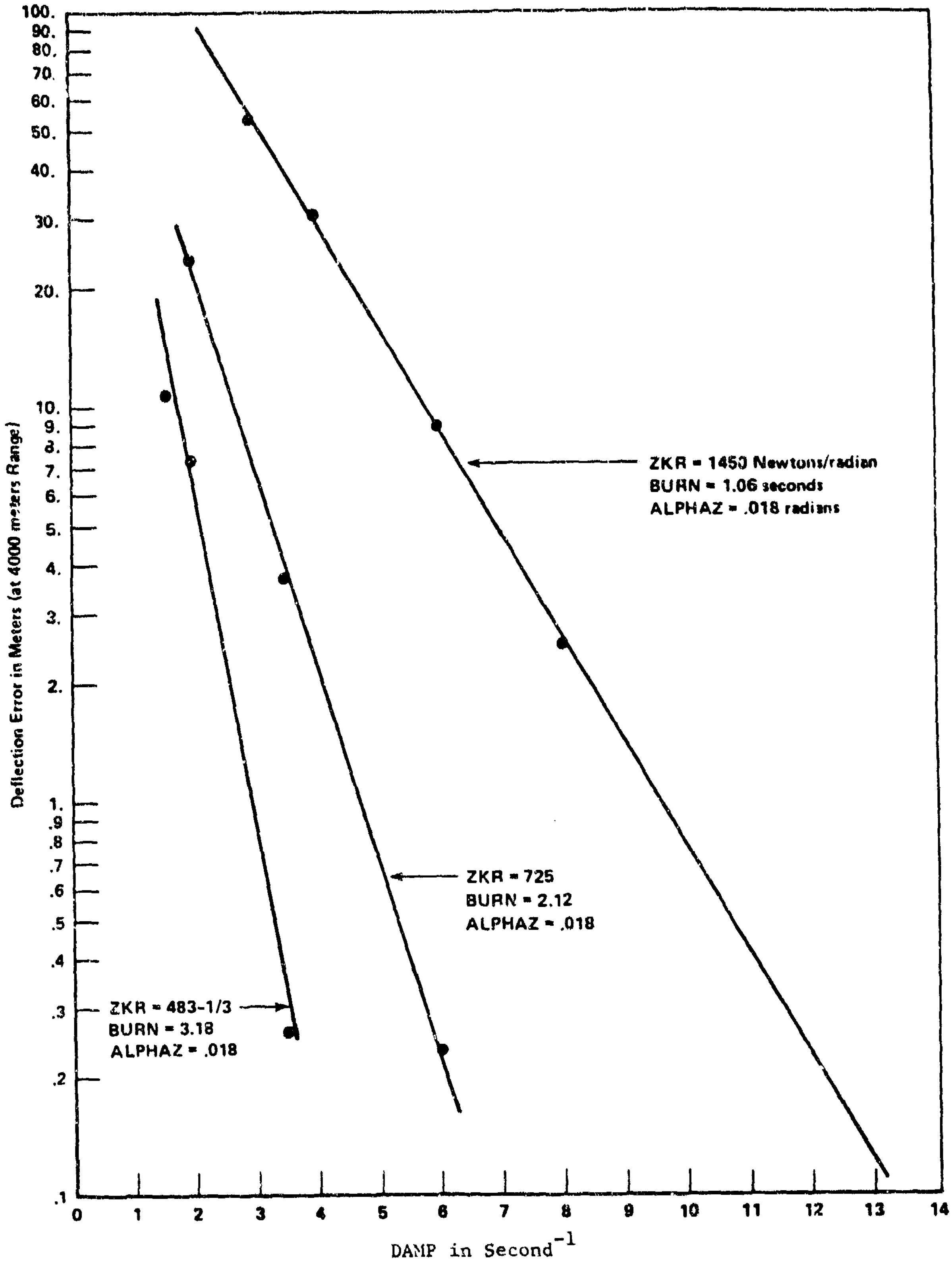

FIGURE 2. BURN TIME VARIATIONS FOR 2.75-IN. FFAR

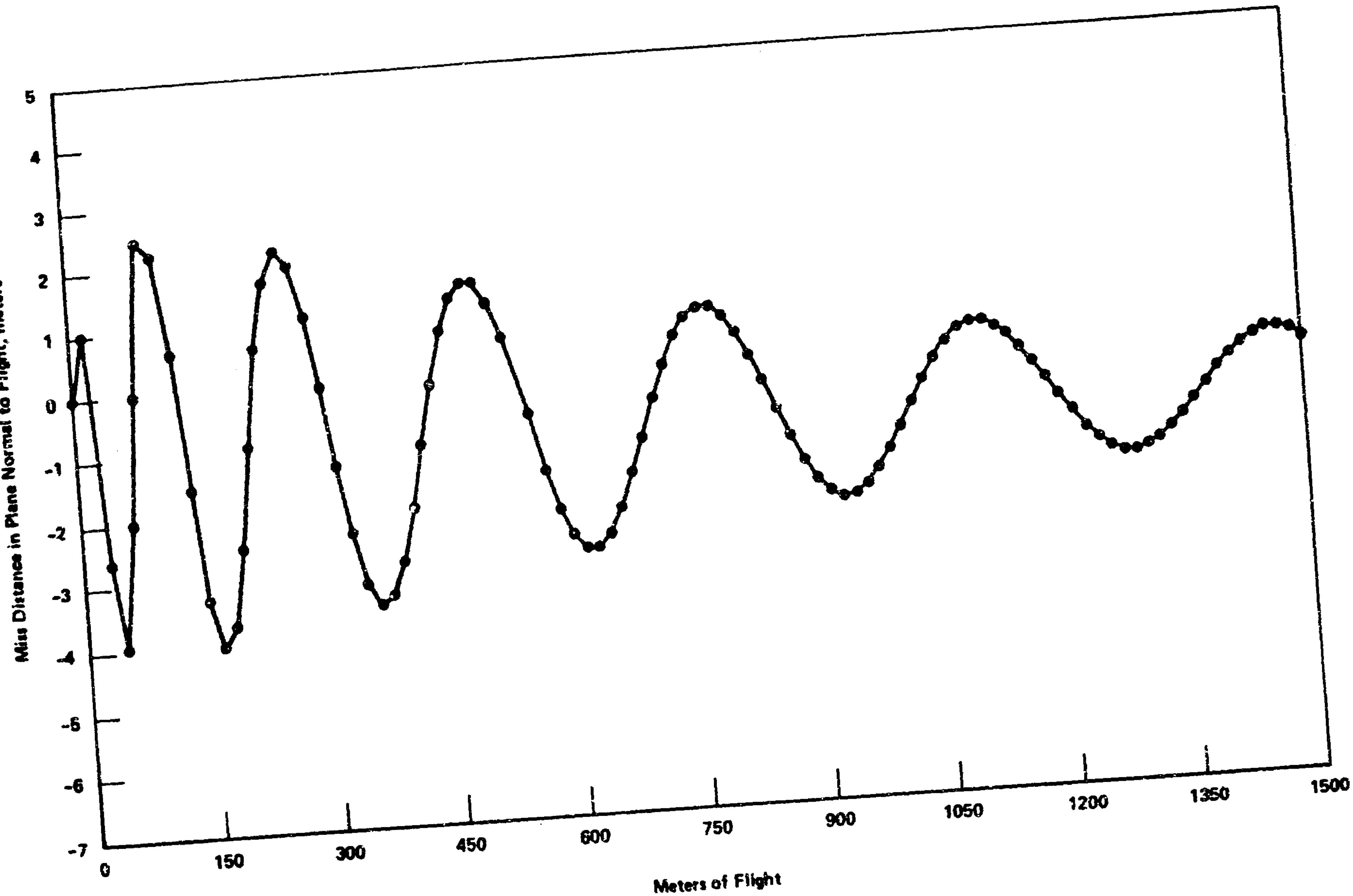

FIGURE 3. NON-BALLISTIC PORTION OF BASE CASE FLIGHT

TABLE 2. CLASSIFICATION OF MLRS ERROR SOURCES

Correctable or Partially Correctable		Not Correctable with SPN	
Source	Importance	Source	Importance
Mal-launch	Major	Total Impulse	Major
Thrust Misalignment	Major	Ballistic Wind	Major
Dynamic Unbalance	Major	Air Density	Medium
Ballistic Coefficient	Major	Time Fuze	Minor
Surface Wind	Medium	Munitions Drift	Minor
		Mal-aim	Medium

The military significance of improvement from 10- to 8-mil error for the MLRS system may be judged by considering Table 3. Suppose the target is self-propelled artillery--a prime MLRS target--at 35 km. The target location error (TLE) will be typically between 75 to 200 m depending on the acquiring assets. Suppose the objective is to kill 30 percent of the target elements--a value commonly used for destruction missions. The ICM pattern radius cited in the Special Study Group report(4) is 125 m, but it could in fact be as large as 200 m. Table 3 then shows the number of rockets which should be launched under various assumptions about the overall accuracy expressed in mils.

TABLE 3. MLRS ROCKETS TO COVER 30 PERCENT OF A SELF-PROPELLED ARTILLERY TARGET AT 35 KM

		TLE = 75 m		TLE = 250 m	
	Pattern Radius:	125 m	200 m	125 m	200 m
Overall MLRS Accuracy	10 mil	17	17	23	24
	8 mil	11	12	18	19
	6 mil	7	8	14	15

What is evident from the table is that an improvement from 10- to 8-mil error would significantly reduce the number of rockets required--whatever the acquiring asset or pattern size. While it is conceded that reductions in the number of fire-and-forget munitions to defeat similar targets would not be as dramatic, the cost savings in <u>either</u> case should be considerable.

The MLRS platform is relatively stable compared to the helicopter platform considered for the 2.75-in. rocket. Consequently, the initial error angle ALPHAZ was not varied over as wide a range in establishing an appropriate MLRS ZKR. It was considered that platform vibration was unlikely to produce an initial error angle greater than 15 mrad.

Similarly, it was considered that the external moment, EMM, would not be as large in the MLRS case as it was for the 2.75-in. FFAR. (The principal difference is the absence of prop wash.) Considering that a 6-mile per hour surface wind is roughly the equivalent of EMM = 0.012, the external moment was varied within the range 0 to 0.1 radians per second squared.

The initial SPIN model runs indicated that a restoring force ZKR in the 1240 to 1500 Newtons/radian range would largely compensate for initial angular errors and external moments as described above. In these runs, the rocket's flight is simulated through the thrust phase and the error values are shown at burnout. Converting this result to the K_r of Freeman(2), these values correspond to $378 \leq K_r \leq 457$ Newton-meters per radian.

In the base case, the correctable (with SPN) component of error is reduced from about 6 mils to 1.56 mils. This refers to range error measured in the plane normal to the trajectory. Consequently, overall system error is reduced from about $\sqrt{8^2 + 6^2} = 10$ mils to $\sqrt{8^2 + 1.56^2} = 8.15$ mils. Because 8 mils is the lower limit to overall error, ZKR = 1500 Newtons/radian achieves about 90 percent of the potential contribution.

Several runs of the SPIN model were then made for sensitivity analysis of this base case. Of particular interest was the variation of the input parameters whose values were not precisely determinable, due to the newness of the MLRS system and the lack of experimental data on the SPN.

Table 4 summarizes sensitivity runs on the MLRS base case. For comparative purposes, range error in mils on the ground plane is used as the figure of merit.

As shown in Table 4, range errors in the sensitivity runs were in the range 2.11 to 1.11 mils. The sole exception occurred when DALFZ was set to -0.025 radian per second. Initial rates of change in the error angle of this magnitude are not likely in the field. Consequently, we estimate that the spinning plug nozzle, if applied to the MLRS rocket, would achieve a range error (correctable component) of 1.6 ± 0.5 mils. The overall system error would thus be improved from approximately 10 mils, to 8.2 ± 0.1 mils. As explained above, such an improvement is of military significance.

To investigate the potential application of the SPN to the OATS conceptual system, several runs with the SPIN (Spinning Plug in Nozzle) model were obtained. The majority of the inputs to the SPIN model described the OATS concept as per information supplied by Mr. J. A. Freeman of Lockheed Missile and Space Company. Initially, it was to be determined if there were a feasible value of the restoring force ZKR attributed to the spinning plug that could produce satisfactory miss distances over a broad spectrum of initial error angles ALPHAZ and external moments EMM.

In the OATS concept, a free-flight rocket passes above the target, between 5 and 15 m above ground level. A sensor in the warhead detects the target and

TABLE 4. RANGE ERROR SENSITIVITY FOR MLRS WITH SPN

Sensitivity Run				Mils
Base Case				1.56
ZIZ	280	→	300	1.73
	280	→	320	1.90
DT	0.001	→	0.0002	1.56
ZKR	1500	→	1000	2.11
	1500	→	2000	1.18
DI	-95.56	→	-100.0	1.52
	-95.56	→	-90.0	1.61
SIN^{-1}	45^0	→	50^0	1.56
(SINB)	45^0	→	50^0	1.56
ACCEL	600	→	500	1.32
	600	→	700	1.78
VZERO	50	→	40	1.55
	40	→	60	1.56
XZERO	675	→	600	1.55
	675	→	750	
QDRAG	0.0004	→	0.0002	1.51
	0.0004	→	0.0006	1.49
GRAV	9.81	→	0.0	1.57
ALPHAZ	0.004	→	0.006	1.85
	0.004	→	0.008	2.14
ARMZ	1.6	→	1.8	1.41
	1.6	→	1.4	1.73
DAMP	1.0	→	2.0	1.11
	1.0	→	0.5	1.86
DARM	0.305	→	0.290	1.57
	0.305	→	0.320	1.54
DALFZ	0.0	→	-0.025	2.63
	0.0	→	+0.025	1.51

initiates a forged fragment warhead, which produces a slug that penetrates the target at high speed. The slug can be directed at the target if its course is not more than 20 degrees off the vertical (downward) direction. From this, one can derive the specifications for a kill of a Soviet T-62 tank. The rocket must hit a trapezoid in the vertical plane, centered on the target, whose height is from 5 to 15 m above the ground, whose bottom dimension is 6.9917 m, and whose top dimension is 14.2711 m. In our calculations, this trapezoid is replaced by a circle of equal area, with radius R = 5.81728 m. The miss distance S must be less than R.

Because the OATS rocket was yet to be built, there was no empirical evidence as to how the air would interact with the rocket to damp its angular motion. Therefore, the input DAMP was the subject of parametric variation. Also, a suitable value for the time interval between calculations had to be established on the basis of resultant accuracy.

The basic conclusion at the end of the preliminary runs of the SPIN (Spinning Plug In Nozzle) model was that OATS was a viable concept with the SPN, but not without it. Because of the conceptual nature of OATS, it was possible that one or more input parameters could be having an undue influence on that conclusion. Accordingly, a sensitivity analysis was performed. Each input parameter to the model was varied, up and down, by at least 25 percent from its "base case" value (Table 1). The choice of restoring force ZKR = 400 Newtons/radian in the base case is a conservative one. It is within experimentally observed values for spinning plugs, and it allows a margin for error. That is, future results tailored to more specific OATS concepts may well show that a lesser value for ZKR would suffice.

The OATS base case deflection error is 0.733 meter at 1 kilometer, which is well within the area needed to score a direct hit. In fact, it leaves room for about 5 mils of independent error from sources that are not correctable with the SPN. Generally speaking, deflection error stayed within 0.75 ± 0.16 meter as the base case parameters were varied individually by $\pm$ 25 percent. (Parameters with 0 value in the base case were varied as follows: GRAV to 9.81 m/sec^2; and DALFZ between -0.1 and +0.1 radians/second.) Simultaneous variations of ZIZ and DI were also attempted, as we simultaneous variations in ARM, DARM, and EARM, with concordant results.

The initial conditions of the base case have an 8 mil error angle <u>into</u> a 12 mph cross-wind. Because a wide continuum of other initial conditions is also of interest, a more detailed sensitivity analysis was performed on the initial error angle ALPHAZ and the external moment EMM due to surface wind. The initial error angle can be anywhere in the range 20 milliradians <u>into</u> 12 mph wind to 20 milliradians <u>with</u> such wind, and deflection error will still be 0.75 ± 0.09. Fixing the error angle at 8 mils, the surface wind can be anywhere from 15 miles per hour, roughly, with or into the error angle while deflection error stays within 1 meter (1 mil at this distance). We conclude that a ZKR of 400 Newtons/radian will be sufficient to produce good performance under a wide range of initial conditions.

The restoring force ZKR due to the plug is of central interest in the design of the OATS rocket. As shown in Figure 4, there is a log-log relationship between the deflection error SDEF and ZKR, provided $100 \leq \text{ZKR} \leq 450$ Newtons/radian. (The R^2 of the regression line fit is 0.99.) At lesser values, the relationship does not hold; other variables would be needed to explain OATS

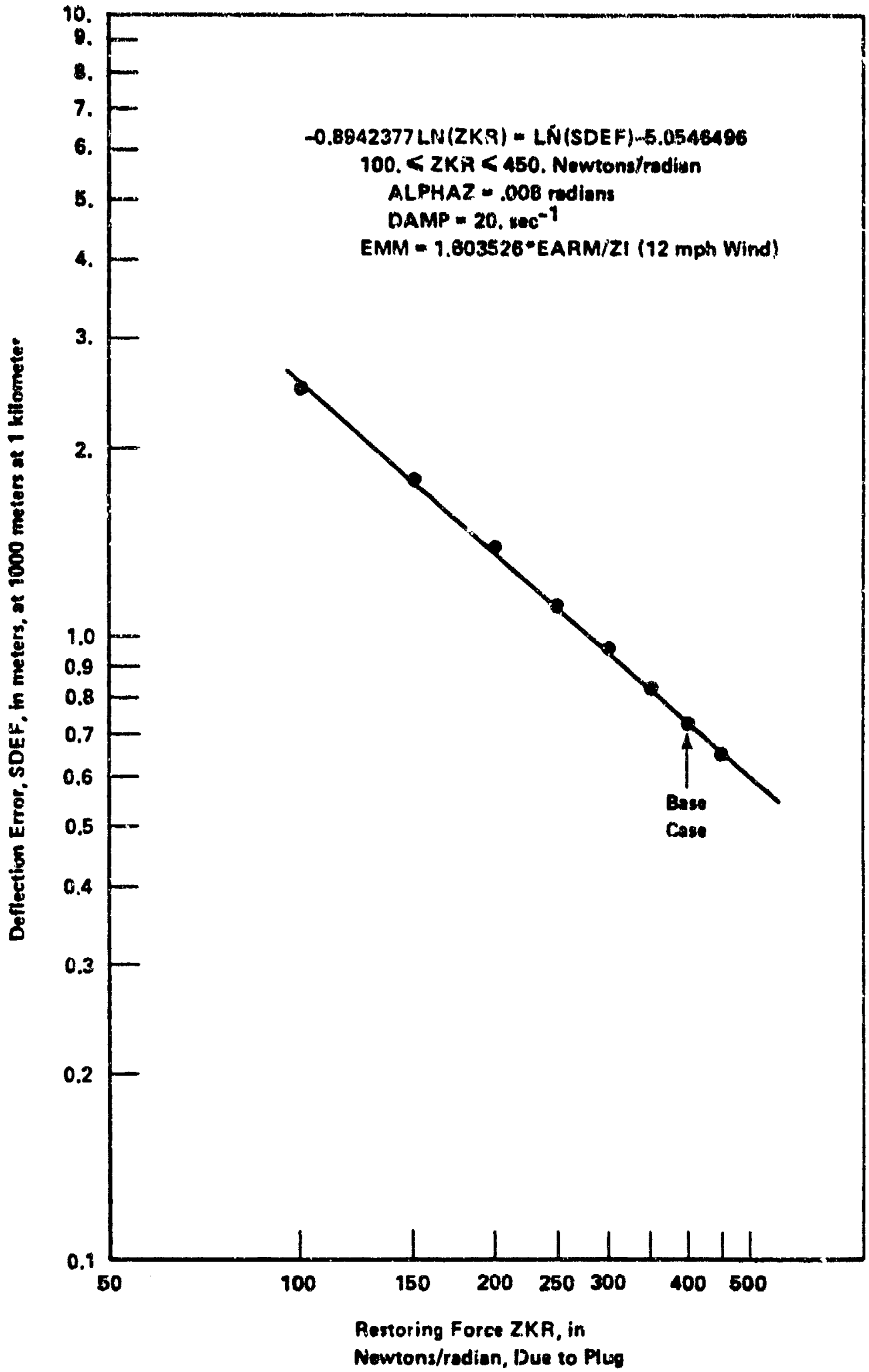

FIGURE 4. EFFECT OF VARYING RESTORING FORCE PER UNIT ANGLE

performance. Thus, the dominant variable determining OATS performance will be under our control provided ZKR is 100 Newtons/radian or greater. At 100, notice that we can still root-sum-of-square some 5 mils worth of independent error not under SPN influence and still hit the trapezoidal basket described earlier.

The miss distances calculated for the OATS base case and variations at a range of 1000 meters are, in general, less than 1 meter. It may be pointed out that these values are also appropriate for a direct-fire weapon with a HEAT warhead. This could be an even cheaper alternative for the medium-range, anti-armor weapon.

CONCLUSIONS AND RECOMMENDATIONS

The major conclusion to be drawn from the analysis is that miss distances can indeed be reduced by use of the SPN. The consequences of this finding, in terms of the gain in military worth and the desirability of adapting the SPN configuration, vary from system to system. In each system, the restoring force constant that will remove most of the correctable error has been estimated. In this section, we consider improved accuracy in terms of military worth, and also what system modifications are required to achieve the advantages of SPN.

It is our judgment that it would not be desirable to convert the 2.75-in. FFAR to an SPN configuration. It does not follow, however, that the SPN is useless for the air-to-ground mission. In fact, it is possible to generate an air-to-ground rocket concept that would be greatly enhanced by SPN. It would have the following properties:

(1) Diameter substantially greater than the 2.75-in. FFAR

(2) Burn time substantially longer than the 2.75-in. FFAR, preferably until the target is reached

(3) Average and final velocities would then also be greater, so that the trajectory would be more nearly rectilinear

(4) Spin-up while the pilot still has the target in his sights, possibly by an auxiliary motor

(5) Improved fire control.

The rocket described by these specifications would look very much like the Navy's ZUNI. Since this study has concentrated on Army weapon systems, it has not included a quantitative evaluation of SPN in ZUNI; but it seems this would be a promising subject for further investigation. An SPN rocket, resembling ZUNI and possible based on it, would be expected to have greater effectiveness than the 2.75-in. FFAR.

The MLRS system is a more favorable case. A ZKR value of 1450 Newtons/radian is sufficient to reduce the error by about 90 percent of the maximum that can be achieved by the SPN. This is a conservative estimate based on experimental results. It is concluded that a plug of this diameter would enable an SPN-equipped MLRS rocket to achieve a militarily significant improvement in accuracy.

Installation of an SPN of this size should require no other major modification in the design of the MLRS. The weight of the plug (approximated as a cone of height equal to its diameter, made of stainless steel having a density of 7.75 g/cm^3) would be about 11.5 pounds. This is less than 2 percent of the weight of the MLRS. There would be some leeway for reducing the plug's diameter before the upper limit of ZKR is encountered.

Rapid spin-up of the plug is not so important a consideration in the case of the MLRS, which is fired from a static platform. It, thus, appears that the SPN-modified MLRS would be more effective than the current model. The reduction in the number of rockets required to achieve a military objective would be about 30 percent while the weight increase of each rocket would only be 2 percent. Assuming that the number of rockets that can be used is limited by logistics, as is expected, the same supply line could achieve a target servicing rate that is increased by more than 25 percent. The ultimate desirability of making this change must be determined by a calculation that includes cost figures.

MLRS is a relatively unfavorable case for SPN application (indirect fire, long ballistic trajectory, curved trajectory). It is remarkable that even in this case the SPN provides a very palpable increase in effectiveness.

Among the competing concepts for a new generation infantry medium-range, anti-armor weapon, the OATS concept is the only one that does not rely on guidance. It is natural to ask whether it can meet the accuracy specifications that are required for an effective weapon. Our results gave an unequivocal answer to this question: without an SPN it cannot; with an SPN it can.

OATS offers an opportunity to design a rocket system that is able to take full advantage of the SPN concept. The benefits of SPN would be greater in such a device than in one in which an SPN is merely retrofitted.

Since there is no experience with the OATS concept, it is hard to say anything about its uncorrectable errors. Again, it appears essential to remove one source of error by spinning up the plug as soon as the rocket has been aimed, but before it is fired. Other uncorrectable errors that are assessed as potentially significant are translation by cross-wind and gravitational drop. Both can be compensated for in the aiming process, and we recommend a fire control mechanism that incorporates cross-wind velocity and target distance data while still permitting the firers to aim visually. Marconi's Simplified Fire Control System (SFCS 600) is one such mechanism.[5]

REFERENCES

(1) Draim, John E., "Attitude Stabilization Using a Rotating Plug Nozzle", Technical Report 158, Aerophysics Laboratory, Massachusetts Institute of Technology, July 1969.

(2) Freeman, J. A., "Signature Characterization--Final Report. Volume II--Spinning Plug Nozzle (SPN) Feasibility Demonstration Program", Technical Report RK-CR-80-5, U. S. Army Missile Command, Redstone Arsenal, Alabama, September 1980.

(3) Judnick, W. E., and Samuel, A. H., "Military Applications of the Spinning Plug Nozzle", Battelle Final Technical Report to Lockheed Missile and Space Company, Huntsville, Alabama, October 31, 1980.

(4) "General Support Rocket System - Volume III: Cost and Operational Effectiveness Analysis (U)", Report ACN 20555, U. S. Army Field Artillery School, Special Study Group (SSG), Fort Sill, Oklahoma, November 1976, (CONFIDENTIAL).

(5) International Defense Review, Special Series, Volume 11, "Armoured Vehicles", pp. 79-81 (Figure 6).